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Contribution from the Bureau of Plant Industry, Wm. A. Taylor, Chief.

THE CONTROL OF ROOT-KNOT.[1]

By ERNST A. BESSEY, *Collaborator*, and L. P. BYARS, *Pathologist, Office of Cotton and Truck Disease and Sugar-Plant Investigations.*

INTRODUCTION.

Attention should be directed to the continual spread of a common disease of plants generally known under the names of root-knot, root-gall, big-root, etc. It occurs as an out-of-doors pest in all except the most northern States, but it is most abundant in the South and Southwest and is everywhere prevalent in greenhouses. It is the cause of serious damage to many crops. The extent of this damage is difficult to estimate, since it is both direct and indirect and in many cases is overlooked entirely. The direct damage is that caused to the growing crops. The indirect damage results from the fact that the presence of the disease makes it impracticable to grow certain crops.

APPEARANCE OF PLANTS ATTACKED BY ROOT-KNOT.

As a rule, root-knot produces no malformations or enlargements on the parts of the plant above ground and consequently is frequently overlooked. However, plants badly infested are dwarfed, wilt readily in hot, dry weather, and are usually a paler green than healthy ones. Where the attack is most severe, plants may be entirely killed. In the case of a mild attack, only a small amount of dwarfing, together with a reduction in yield below the normal, is noticeable. Sometimes even the dwarfing is absent, and the reduction of yield is not noticed. Since the disease is widely prevalent in some

[1] This bulletin is based on the work of Dr. Ernst A. Bessey while he was a member of the scientific staff of the Bureau of Plant Industry. The manuscript, which was originally prepared by him, has been recast and put into form for the Farmers' Bulletin series by Mr. L. P. Byars, who is now continuing the root-knot investigations of the bureau.

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districts, the reduced yield is supposed by the growers to be the normal one.

On examining the roots of an infested plant the presence of the disease is usually very easily detected. Depending upon the severity of the attack, the fine feeding roots, as well as some or all other roots, will be found to be greatly enlarged at various points. These enlargements may be scattered or they may be so close together that the whole root system is abnormally thickened. Hence, the disease has been given such descriptive names as root-knot and big-root. Plants affected in this way are frequently said to have clubroot,

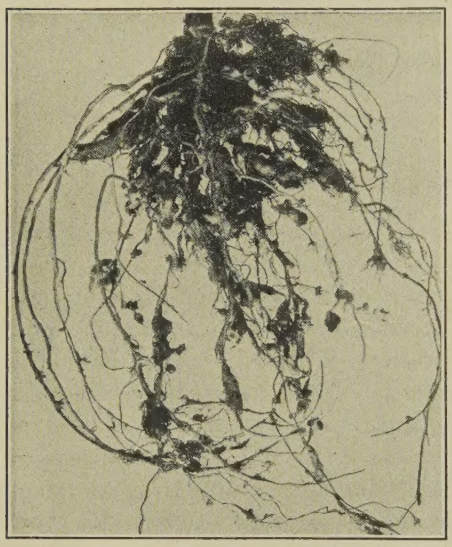

FIG. 1.—Root-knot of the cowpea, showing enlargements caused by the gallworm. With the exception of the Iron and Brabham varieties, this plant is very susceptible to root-knot, and the use of susceptible varieties as green-manure crops in peach orchards and in rotations just preceding cotton is to be avoided. (Photographed by W. W. Gilbert.)

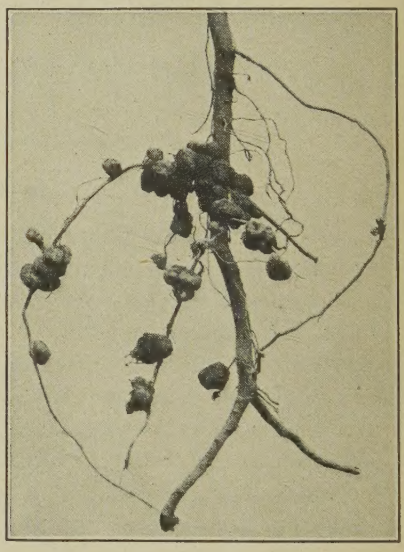

FIG. 2.—Spherical nodules on cowpea roots produced by beneficial nitrogen-fixing bacteria. These enlargements should not be confused with the injurious root galls shown in figure 1 that are caused by the gallworm.

although the true clubroot is a disease due to an entirely different cause and is confined to plants of the mustard family. Root-knot enlargements in legumes, such as the cowpea and clover, are also sometimes confused with the beneficial nodules caused by the nitrogen-fixing bacteria which live in the roots of these plants. Nodules produced by the nitrogen-fixing bacteria are spherical or lobed, small or medium sized, and attached to the side of the rootlets, while the root-knot parasite causes a swelling of the root. The pronounced difference in appearance between the injurious root enlargements and the beneficial root nodules on the cowpea is shown in figures 1 and 2, respectively.

The enlargements of roots diseased with root-knot, as seen in figures 1 and 3, interfere with the transfer of water from the fine feeding roots to the stem and leaves, with the result that in rather dry weather on a hot day the plants may wilt through failure to secure the proper quantity of water, even though the soil may be quite moist. Furthermore, the diseased tissues are quite watery and easily permit

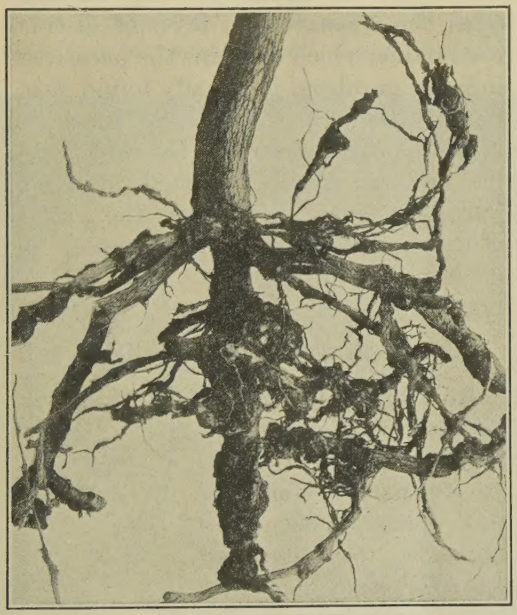

FIG. 3.—Root-knot of cotton. The root-knot parasite may occur in such small numbers as not to be very serious in itself, yet the injuries to the roots caused by it furnish a vulnerable point of attack for the wilt fungus; hence, root-knot in combination with the fungous disease greatly reduces the yield. (After W. A. Orton.)

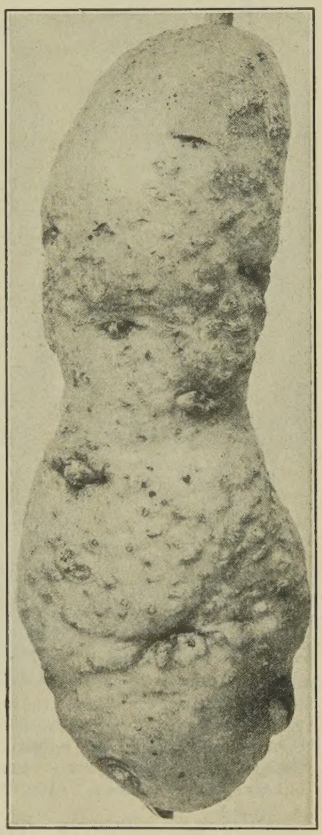

FIG. 4.—A potato badly infested with gallworms. The roughened, warty, and discolored surface of the tuber are the external signs which indicate the presence of the parasite in the interior. Such diseased potatoes are unfit for table use and should never be used for seed purposes. (After W. A. Orton.)

the entrance of fungi or bacteria which cause decay, so that the death of the plant may be due immediately to the nematodes themselves or to other parasites that gain entrance to the plant through the diseased tissues. A good example of this is often seen in the case of cotton, on which the root-knot parasite alone may be present in such small numbers as not to be particularly harmful beyond reducing the yield somewhat. Yet the injuries to the roots due to this parasite make it possible for the fungus that causes the wilt of cotton (black-root), when present, to gain entrance to the roots much more readily than if the root-knot parasite were absent. Thus, root-knot in combination with the fungous disease greatly reduces the crop.

It is not always the roots that bear the most conspicuous and harmful effects of root-knot. In certain tuberous plants like the Irish potato, the swellings on the rootlets may be small, while the tubers when thoroughly infested with the disease are much roughened, discolored, and warty on their surfaces, as shown in figure 4. By cutting open these potatoes, a layer of discolored tissue, which contains the parasites in large numbers, is usually found just beneath the skin (fig. 5). Such tubers are not only undesirable for table use, but are also wholly unfitted for seed purposes, since they carry the cause of the disease and spread it into uninfested districts.

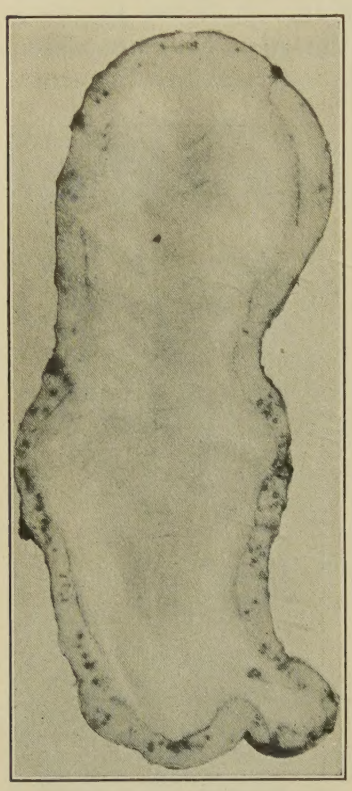

FIG. 5.—Half section of a potato invaded by the gallworm. Just beneath the surface of the tuber is a ring of discolored tissue which contains a large number of these worms. Planting such tubers quickly spreads the disease. (After W. A. Orton.)

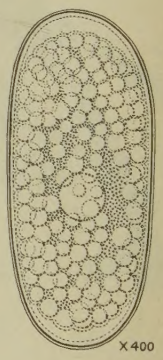

FIG. 6.—A newly deposited egg of the gallworm, magnified 400 times. These eggs are extruded in large numbers, some females laying as many as 500. Because of their tough covering, the eggs are resistant to chemical treatment and adverse soil conditions. (After N. A. Cobb.)

CAUSE OF ROOT-KNOT.

Root-knot is caused by a minute animal, *Heterodera radicicola*. In the earlier stages of its development this animal is wormlike, and for this reason has been called an eelworm. On account of its production of galls, it may be called the gallworm. It belongs to the group of animals more correctly known as nematodes, many of which are injurious to plants, while numerous others attack animals. The particular species under consideration is found widespread over most of the temperate and tropical parts of the world where the conditions are favorable for its development. Its life history[1] is as follows: Hatching from an egg which is usually less than one two-hundred-and-fiftieth of an inch in length, it is a small, wormlike creature between three and five times as long as the egg; that is, about one-eightieth to one-fiftieth of an inch in length. The diameter

[1] Additional information concerning the life history of this parasite, with a list of susceptible plants and details of experiments in controlling the nematode in the southeastern United States, may be found in Bulletin 217 of the Bureau of Plant Industry, entitled "Root-Knot and Its Control," by Ernst A. Bessey, issued Nov. 21, 1911.

of the body is about one-thirtieth of the length. On account of their minuteness, these nematodes are invisible to the unaided eye. They move through the soil with considerable activity, and on finding a root, preferably a young feeding root, bore their way into it, usually near its tip. Once inside, the young nematode ceases its active movements, begins to enlarge, and by means of a hollow, spearlike organ within its mouth absorbs its nourishment from the root. A greatly magnified egg is shown in figure 6, while in figure 7 both eggs and larvæ magnified about 30 times may be seen.

FIG. 7.—Illustration made from a microphotograph of the eggs of the gall-worm and the young worms just hatched, taken from a potato. It is in this worm stage that the parasite moves through the soil and enters the roots or tubers of plants. (After F. B. Headley.)

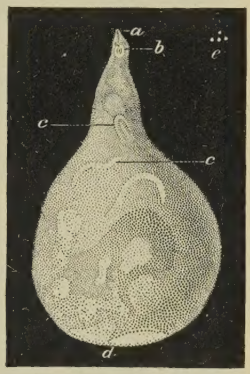

FIG. 8.—A female of the gall-worm (*Heterodera radicicola*), magnified 85 diameters: *a*, Mouth; *b*, spherical sucking bulb; *c*, *c*, ovaries, as seen through the body wall; *d*, anus; *e*, small white spots showing approximately the natural size of these worms. During the egg-laying period they are usually a glistening white and can be readily seen with the unaided eye by carefully breaking open an infested gall. (After N. A. Cobb.)

The presence of the nematode in the root irritates the tissues in such a way that the root enlarges, forming a swelling that may be two or three times as thick as the diameter of the root above or below. If many nematodes are present in the root, the swelling may become very large, especially as the root increases in age. The nematode within the root increases in thickness more rapidly than it does in length, so that eventually the mature female nematode is almost pear shaped and large enough to be visible to the naked eye, becoming from one-fortieth to one-twenty-fifth of an inch in diameter. When a root badly infested with these nematodes is broken open at this stage, the mature females, as shown in figure 8, can frequently be observed as minute, pearly white, rounded bodies from one-

fourth to one-half the diameter of the head of a common pin. It requires about four weeks for the female to reach full development and begin laying eggs. The female is capable of laying more than 500 eggs, each of which may hatch into a wormlike larva, as mentioned above.

FIG. 9.—A sugar beet affected with root-knot. In certain sections of the Southwest the growing of sugar beets has been prevented by this disease.

The males are rarely seen except when searched for at just the right period. Their development up to a certain stage is like that of the female; that is, the larva enters the root in the same way and enlarges within it, but after becoming much elongated and shedding a skin it bores its way out of the root into the soil again. It is then a wormlike animal one-sixteenth to one-twentieth of an inch in length, but not over one-fortieth as thick as it is long. It is practically invisible to the naked eye.

In the warmer climates, such as southern Florida, southern Texas, and parts of California, it is possible for the nematodes to pass through as many as 10 to 12 generations in a year, but in the cooler climates the number is less. The number of generations is governed by the temperature, since the nematodes do not develop except when the soil is warm. Thus, in northern Florida December, January, and February are months in which little nematode injury occurs. In South Carolina the comparatively quiescent period lasts from the middle of October to the middle of April, while in New York, Michigan, and Colorado the active period is probably not much longer than the three warmest summer months.

PLANTS ATTACKED BY ROOT-KNOT.

The root-knot nematode attacks a large number of plants of widely different types. The kinds of plants on which it is known to occur number nearly 500, and doubtless future observations will greatly

extend this list. Among those subject to attack are many in which the nematodes inflict no visible injury upon the plants, being found only in a few of the smaller roots in such small numbers that they are negligible, as far as the plant is concerned. Many of the common weeds belong to the class of plants which harbor the nematodes and at the same time show few of the symptoms. However, such plants are dangerous from the farmer's standpoint, since they help to keep the soil stocked with the nematodes. When it is considered that one female may produce more than 500 eggs, it is evident that not many individuals are required to keep the ground thoroughly

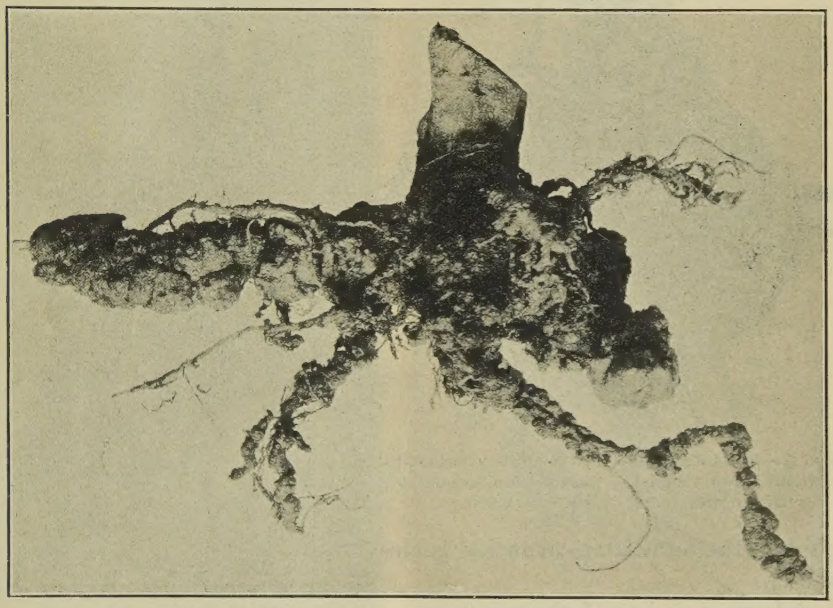

FIG. 10.—Squash roots affected with root-knot. The entire root system has become infested with the parasite; hence, the proper amount of food material does not reach the parts of the plant above ground.

infested. The young nematodes are able to exist in the soil for more than a year, working their way through it during the warm weather in search of roots into which they may enter. For this reason it is important to keep the ground free from the plants upon which the nematodes feed.

Besides the plants that are only slightly infested we find some in which the nematode galls are very abundant on the roots, yet with no apparent damage noticeable in the crop. Such plants, perhaps, make up the majority of the susceptible ones. There is a third class, however, in which the nematode injury is very severe and easily noticeable. Such plants make poor growth, are stunted, give reduced crops, or are killed prematurely, while the roots are found to be masses of swollen structures scarcely recognizable as roots. In badly infested

areas the sugar beet, squash, tomato, lettuce, cantaloupe, and celery, as illustrated in figures 9, 10, 11, 12, 13, and 14, present all the root symptoms described for this third class of plants. Somewhat less conspicuously, the effect of the parasite upon woody plants, such as the grape, willow, and fig, is shown in figures 15, 16, and 17. In figures 18, 19, and 20 the result of gallworm infection of the primrose,

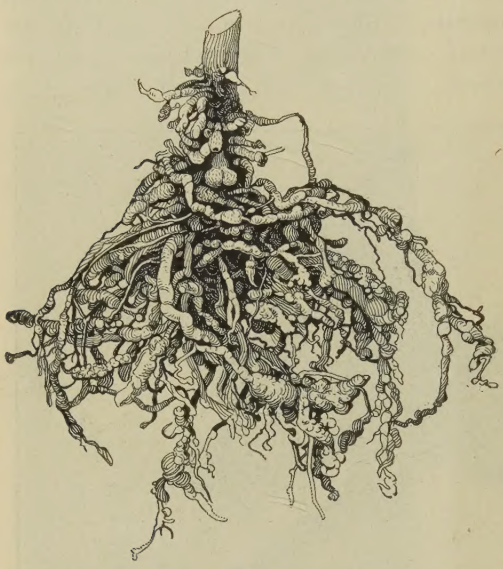

FIG. 11.—Roots of a tomato plant completely invaded by gallworms. Most varieties of tomatoes are severely attacked by the parasite. (After George F. Atkinson.)

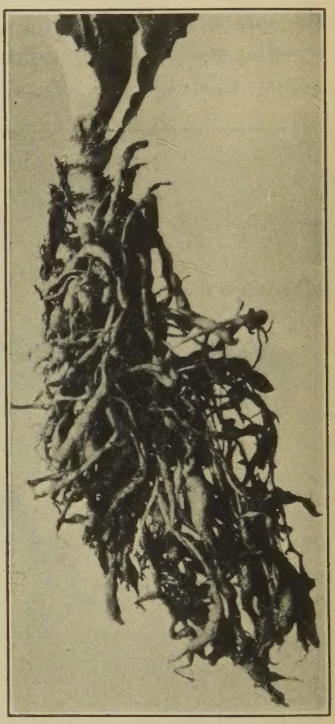

FIG. 12.—Lettuce roots infested with the gallworm. Almost all other common garden plants are likewise attacked. Their roots furnish excellent feeding and breeding places for the parasite.

chrysanthemum, and carnation is clearly shown.

A large number of the commonly cultivated plants are more or less subject to the disease. The classified list which follows includes the more important highly susceptible plants. These should never be grown on infested fields or transplanted from any field that may possibly contain the parasite.

Field crops:
- Alfalfa.
- Clover.
- Cotton.
- Cowpea (except Iron, Brabham, and hybrids of Whippoorwill crossed on Iron.)
- Field pea.
- Flax.
- Pumpkin.
- Soy bean.
- Sugar beet.

Field crops—Continued.
- Sugar cane.
- Sweet potato.
- Tobacco.
- Vetch.

Ornamental and drug plants:
- Begonia.
- Cineraria.
- Clematis.
- Coleus.
- Dahlia.
- Hollyhock.

Ornamental and drug plants—Continued.
- Ginseng.
- Goldenseal.
- Peony.
- Rose.
- Sweet pea.
- Violet.

Truck crops:
- Asparagus.
- Bean.
- Cantaloupe.
- Carrot.

Truck crops—Continued.
Celery.
Cucumber.
Eggplant.
Garden beet.
Garden pea.
Irish potato.
Lettuce.
Muskmelon.
Okra.
Onion.
Pepper.
Salsify.
Spinach.
Strawberry.
Tomato.

Woody plants:
Almond.
Catalpa.
Cherry.
European elm.
Fig.
Old World grapevine.
Mulberry.
Peach.
Pecan.
Persian walnut.
Weeping willow.

Besides the above-listed plants, most of the common weeds are attacked by the nematodes, although usually not very severely.

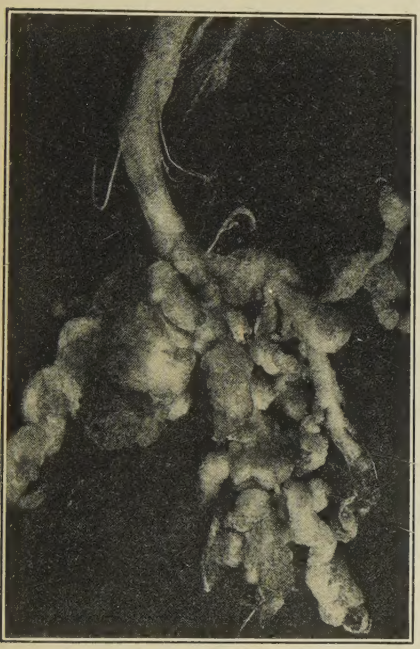

FIG. 13.—Roots of a cantaloupe plant, showing enlargements due to the gallworm. Other truck and field crops are similarly attacked and should never be planted two successive years on infested land.

FIG. 14.—Root system of celery thoroughly infested with the root-knot nematode. To control this parasite, at least a 2-year rotation with resistant crops is necessary.

Such weeds, however, are a constant source of danger to the farmer, as they help to increase the number of nematodes in the soil. An abundance of weeds is a sign of poor agricultural practice anywhere, but weeds become doubly dangerous where they not only do harm by crowding out other plants and using up food intended for them, but also multiply a pest which may later destroy the crops planted.

PLANTS NOT ATTACKED.

Fortunately, many plants of economic importance are known to be free from the attacks of root-knot. As will be shown later, advantage is taken of this fact in controlling the disease. The

following list includes the more important cultivated plants which, so far as known, are seldom or only slightly affected by the nematodes and may be used in crop rotations with the expectation of greatly reducing the number of gallworms.

Barley.	Corn.	Pearl millet.	Timothy.
Beggarweed.	Crab-grass.	Redtop.	Velvet bean.
Brabham cowpea.	Iron cowpea.	Rye.	Wheat.
Broom-corn millet.	Peanut.	Sorghum.	Winter oats.

CONDITIONS FAVORING ROOT-KNOT.

Root-knot is seldom found in heavy soils, apparently because it is difficult or almost impossible for the young nematodes to make their way from one root to another through such soils. It is prevalent, however, in light soils, especially those of a very sandy nature. There is therefore much more risk of infestation in planting susceptible plants on light, sandy soil than on those which are heavy or stiff. Where the land is water-soaked for a considerable period of the year these nematodes are not abundant or do not occur at all, nor are they found, on the other hand, in land that is exceedingly dry. They live in greatest abundance in the light, sandy soils of the South, where they have the proper texture of soil combined with a desirable amount of moisture and a long, warm summer. This fact explains the universal occurrence of the nematodes in

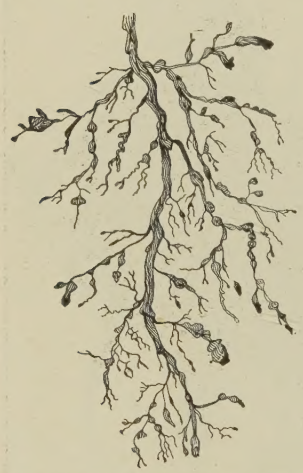

FIG. 15.—Root system of the Black Hamburg grape, showing small swellings due to the gallworm. The parasite causes much damage every year to many crops which the grower supposes are normal. (After J. C. Neal.)

FIG. 16.—Roots of a weeping willow diseased with root-knot. Many ornamental plants are subject to this disease and should not be planted in soil known to be infested with the gallworm. (After J. C. Neal.)

FIG. 17.—Roots of the fig, showing swellings caused by the root-knot nematode. Most varieties of the fig are especially susceptible to the attacks of this parasite, which thrives in moist, sandy soils suitable for fig growing. (After J. C. Neal.)

greenhouses, where conditions for their growth approximate the ideal. However, the disease is found where the soil is of the proper type even in regions where the temperature goes many degrees below zero in the winter, as, for example, at points in Michigan, Nebraska, Colorado, and Utah.

METHODS OF SPREADING THE PARASITE.

The larvæ of the nematode are capable of moving through the soil only very slowly, perhaps not more than a few feet each year. Yet this movement suffices to permit them to descend to a sufficient depth in the soil to escape drought and frost. It is not primarily by its own efforts, however, that the parasite is spread. It may be transported from field to field in a given district along with the soil that clings to agricultural implements, to the feet of domestic animals or man, or to transplanted plants. Too much care can not be exercised to prevent the distribution of infested plants or soil on plants to areas which are free from the pest. Garbage, manure, or waste matter of any kind containing parts of diseased tubers or roots may spread the parasite and should never be placed on uninfested land. The pest is also frequently carried to other fields by means of irrigation water and surface water resulting from heavy rains.

FIG. 18.—Primrose roots badly infested with the gallworm. Greenhouse soils kept at a mild, even temperature furnish excellent conditions for the growth and rapid increase of this parasite. (Drawing furnished by N. A. Cobb.)

FIG. 19.—Chrysanthemum, the roots of which are infested with the gallworm. Plants severely attacked by this parasite are often dwarfed; they grow slowly and serve as breeding places for the nematode. (Drawing furnished by N. A. Cobb.)

FIG. 20.—Carnation plant, the roots of which are much distorted and swollen as a result of gallworm infection. Many greenhouse plants are similarly attacked when grown in soil which has not been sterilized. (Drawing furnished by N. A. Cobb.)

The most common method of transporting the disease from one locality to another is through shipments of nursery stock, tubers,

and bulbs. Particularly in the Southwest have numerous observations shown that peaches, figs, and Old World grapevines are the means by which new areas become infested. This suggests that no nursery stock should be accepted until it has been found free from nematodes, and, if suspected of having come from infested districts, it should be planted on a separate part of the farm until upon examination later it is found to be free from the trouble. In certain irrigated districts of California and Nevada[1] seed potatoes have been chiefly instrumental in introducing and spreading the gallworm. In attempting to control this disease it is absolutely essential to plant only uninfested tubers. To use tubers showing no superficial evidences of the disease is not enough, but clean and healthy seed should be selected from fields where a critical inspection shows that the disease has not been present. It naturally follows that potatoes which are to be used for seed purposes should be secured from uninfested localities, preferably from States along the northern border from Minnesota to Maine, where the extreme temperatures practically prevent the occurrence of the nematode as an out-of-door pest. In the South and East, tomatoes and tobacco plants, as well as various classes of nursery stock, such as the fig, peach, and mulberry, are means through which the parasite is known to be most frequently transferred into new localities. The prevalence of the pest in ginseng plantations is undoubtedly due to the transplanting of rooted seedlings from infested soil and to the use of seeds which were packed in damp infested dirt.

METHODS OF CONTROLLING ROOT-KNOT.

GREENHOUSES, SEED BEDS, ETC.

In greenhouses the method that is most efficient is that of steaming[2] the soil by passing steam into perforated 1½-inch pipes laid lengthwise in the benches from 1 foot to 1½ feet apart and at a depth of 1 foot below the surface of the soil. Eighth-inch holes are made on the under side of the pipes at intervals of about 6 inches. The soil can be thoroughly heated in the course of an hour or more, depending on the steam pressure, until all animals, as well as most of the fungi causing plant diseases, are killed. It has been found desirable to cover the soil with a canvas or a layer of straw held on by boards laid closely together, in order that the steam may not merely blow through the soil at certain points but may rather be distributed evenly throughout the bed. The higher the steam pres-

[1] For more detailed information regarding the gallworm as it occurs on potatoes in the irrigated districts, see Circular No. 91 of the Bureau of Plant Industry, entitled "The Nematode Gallworm on Potatoes and Other Crop Plants in Nevada," by C. S. Scofield.

[2] For a more detailed explanation of the method outlined in this bulletin and for an account of the inverted-pan method of steaming soils, see pages 34 and 35 of Bulletin No. 158 of the Bureau of Plant Industry, by W. W. Gilbert.

sure, the more quickly the proper temperature is attained, with the further advantage that at high pressures the soils do not become so water-logged as they do if low-pressure steam is used. A convenient method often employed to determine whether the steaming has continued long enough is to bury potatoes at various points in the surface of the beds. When these are found to be cooked, one need have no fear that any nematodes will remain alive. Indeed, they probably perish long before the potatoes heat through. Where steaming is impossible, greenhouses may still be freed from nematodes by removing the infested soil, whitewashing the benches with boiling-hot fresh whitewash and refilling them with fresh soil taken from some point where, by the observation of susceptible plants, it has been found that no nematodes are present. Fresh soil that is entirely or nearly free from the nematodes may be secured from low bottom land or any land that is flooded for a considerable period, preferably two to six months each year.

These methods apply, of course, only to beds which contain no living plants. It is impossible to formulate a rule of procedure that will be satisfactory in all cases in freeing beds of living plants from nematodes. If the plants are capable of being transplanted, they may be removed from the soil, washed, and all diseased roots cut off, cutting back the tops to correspond, and then transplanted to fresh soil. Before replanting it is well to soak the roots for half an hour or more in a solution of 1 part of 40 per cent formaldehyde in 100 parts of water, in order to kill any nematodes that may be present in the dirt adhering to the surface.

GINSENG PLANTATIONS.

Special attention should be given to the methods of combating the nematodes in the ginseng industry. These nematodes are introduced into the ginseng bed usually in one of three ways: (1) By means of the damp soil in which ginseng seeds are often shipped; (2) in affected seedlings bought from a grower who has the disease on his place; and (3) in the soil clinging to tools, men's shoes, etc. To avoid the introduction of the trouble care should be taken that the soil in which seeds are packed is so disposed of that there is no chance of infecting other soil. The seeds should be washed, perhaps with the addition of a small amount of formaldehyde to the water, but should not be soaked for a long period in this solution until it is determined how long a time is necessary to kill the seeds. Seedling plants should not be bought from a grower in whose beds the disease is present. If it is suspected that he may have the disease in his beds, each seedling should be examined, and if any roots are found affected the wisest procedure would be to refuse the whole shipment. If this can not be done, the diseased plants should be destroyed and the healthy

ones washed in a dilute solution of formaldehyde (1 part of 40 per cent formaldehyde to 50 parts of water) and planted in an isolated bed. If no disease appears in this bed within the next year or two, it can be assumed that the disease was not brought in. Until this period is passed, however, no tools should be used on other beds without first scouring off the dirt from this bed and dipping them in a solution of 1 part of formaldehyde to 50 parts of water, so that there may be no chance of transferring the nematodes. If the disease is present in one of the beds it is possible that the following treatment may save some of the plants, though the details of the process have not been thoroughly worked out: All the plants should be dug and carefully washed, so that all the roots are exposed. Those that are badly knotted should be dried and sold as fiber, but those on which only a few of the lateral feeding roots are diseased should have these roots removed and dried for fiber. The plants should then be dipped in a formaldehyde solution (1 part of 40 per cent formaldehyde to 50 parts of water) for 10 to 15 minutes, to destroy such nematodes as might be adhering to the surface, and then planted out in fresh beds known to be uninfested.

ORCHARDS.

For fields in which plants are permanently growing, for example, in orchards and gardens of ornamental shrubs, no very satisfactory treatment has been worked out. It has been found that by cultivating the fields thoroughly and at the same time fertilizing them highly, particularly with stable manures and commercial fertilizers rich in potash, so that the plants are induced to make rapid root growth, the roots will frequently go below the level at which most of the nematodes are present and will develop faster than the nematodes can produce their knots. This permits the development of fairly good crops. It has been shown that peach trees affected with the disease, if treated in this manner, can sometimes be caused to outgrow the trouble to a considerable extent. More often the renewed vigor results in only a temporary relief, as the new root growth subsequently becomes invaded by the parasite and the plant relapses into its former condition.

Where only a few trees in a young orchard are affected (and this is commonly the case when partially infested nursery stock is planted on uninfested land), they should be removed and destroyed. The surrounding soil, including an area well beyond that occupied by the infested roots of the removed tree, should then be treated with a solution of formaldehyde (1 part of 40 per cent formaldehyde to 50 parts of water) at the rate of about 2 to 3 gallons per square yard. In this way the further spread of the disease is prevented, and nematode-free trees may be replanted after at least one year's delay with little fear of their becoming infested.

One means of preventing root-knot in peach orchards practiced in certain parts of Florida is that of grafting the peach on the native wild plum. This method has proved successful from the standpoint of the disease, because the wild plum is resistant to root-knot. As a general horticultural practice, however, grafting the peach on the wild plum has not given satisfactory results.

However successful any of the above methods may be, it is very evident that the proper and safe way to control the disease in orchards is never to plant trees on land that is known to be or suspected of being infested with nematodes and to use only uninfested nursery stock. It is far better to wait the required number of years to free the land from the pest than to take the risk of having the trees remain several years without any appreciable growth, as is too often the case where nematodes are abundant. To plant a very susceptible crop, such as the ordinary varieties of cowpeas, melons, cucumbers, or tomatoes, in a field that is later to be occupied by an orchard or other permanent crop is highly undesirable. The nematodes will multiply in great numbers on the susceptible plants and so infest the soil that the permanent crop will be seriously injured. For this reason many farmers in the South believe that either the growing of cowpeas before planting peach trees or the use of cowpeas as a cover crop after the peach orchard has been planted is a dangerous practice. Such is the case if the cowpeas are not of a resistant variety.

FIELDS NOT USED FOR PERMANENT CROPS.

The most satisfactory method of combating the disease is that in which the infested fields can be planted to nonsusceptible crops for a period of years. To be sure, nematodes can be starved out entirely in two years or a little more if the ground is kept absolutely free from vegetation of all kinds, but this is impracticable on a large scale and in many regions, because of the consequent erosion of the soil, the leaching out of the food substances, and the loss of money due to the nonproductivity of the field for that period. However, by making use for about three years of a rotation in which the plants used are not susceptible to the disease, the cost of controlling the nematodes may be considerably reduced, while the land may be actually enriched. Not only is the nematode subjugated by the proper system of rotation, but the same is true of other plant diseases which increase from year to year when the land is repeatedly planted to one crop. As a general agricultural practice, rotation has everywhere proved a necessity to successful farming.

The rotations that have been found to be desirable are those in which a summer leguminous crop alternates with a winter grain. In making these rotations it is, of course, necessary that the crops grown in the summer be free from the attacks of the root-knot nematode. By using leguminous crops the land is enriched while the process is

being carried on, and by selecting the proper crops the rotation can be carried on at a profit. The summer crops which have been found most satisfactory for this purpose are corn, velvet beans, Florida beggarweed, and cowpeas of the Iron or Brabham varieties, which are highly resistant. Corn should be planted at the usual time in early spring and followed later by one of the two resistant varieties of cowpeas, which are drilled between the corn rows. Corn and cowpeas planted in this manner make a very desirable combination, as they permit clean cultivation. Of the legumes, beggarweed has the disadvantages that its growing season is so long that it does not permit seed production except in the extreme Southern States and that its seed is expensive. In certain parts of Florida the Brabham and Iron cowpeas are subject to injury by root-knot. While this injury is not severe enough to destroy the plants, yet it is inadvisable to grow even these resistant varieties in such places, since by so doing the nematodes are increased. In other parts of the South the only disadvantage of using cowpeas lies in the difficulty of securing unmixed seeds of the resistant varieties. If seeds of other varieties are present, abundant infestation will result. The three legumes mentioned seem to be the best that can be recommended, although the Spanish peanut appears also to have qualities which should fit it for similar use. By referring to the list of immune plants, it will be seen that other immune summer crops could be used, such as sorghum, millet, or redtop.

The two most successful winter crops in the South are winter rye and winter oats, although the latter does not seem to be satisfactory on many of the very light, sandy soils. In certain latitudes the grain may be allowed to ripen; then the velvet beans or beggarweed should be sown. This should be cut for hay in time to permit the ground to be prepared for sowing the winter grain.

In view of the above facts the following rotations are suggested for fields infested with root-knot: In the fall sow winter rye so early that it can make a good growth before it is necessary to plow the land for the next crop. Turn under the rye as green manure in early spring and plant corn, later placing cowpeas (the Iron or Brabham varieties) in the drill between the rows. The second fall sow winter grain, preferably oats, which may be allowed to ripen or may be cut for hay while green. Follow this with either the Iron or Brabham variety of cowpeas, which can be sown broadcast, or, better, in 2-foot drills, where they can be cultivated. Harvest the cowpeas as hay, and if a 3-year rotation is desired sow winter grain, allow it to ripen, and again broadcast Iron or Brabham cowpeas to be cut as hay. Barley or wheat may be substituted for the oats and rye, and (in the second and third years) velvet beans and beggarweed may be broadcasted instead of cowpeas.

It is possible to starve out the nematode by the 2-year rotation if it is carried on very carefully. However, it seems better to use the 3-year rotation. The completeness with which the nematodes are exterminated by the process here outlined depends largely upon the care with which the work is performed. Thus, if weeds or volunteer plants from a previous susceptible crop, such as Irish potatoes, are allowed to be present during the summer, the nematodes may be harbored by these and the extermination will not be complete. If the field is subject to overflow by surface water from adjacent infested land, fresh infestation will be the result and the value of the rotation will be lost. The same result will follow if infested soil is introduced on plows, cultivators, wagon wheels, horses' hoofs, etc. It would be desirable to dig a ditch 2 feet wide and a foot or two deep along those sides of the field that border infested fields which are higher up. Besides preventing overflow the ditch will make a kind of natural boundary, across which animals or implements should not be allowed to go.

In regions of general infestation, as in many parts of the South, the reinfestation of fields which have been freed of nematodes is very likely to occur. For this reason it is desirable to introduce a 2-year nematode-extermination rotation, such as that outlined above, every four or five years. In this way serious infestation is prevented. In such a rotation it would be desirable to plant the most susceptible crops immediately after the field has been cleared of nematodes and to follow them by those which are less susceptible until the time comes to apply the extermination rotation again.

SELECTING RESISTANT VARIETIES.

Among the cultivated crops certain strains or varieties are known to be highly resistant, if not immune, to nematode attack. These are (1) the Iron and Brabham varieties of cowpeas, which, if not mixed with other varieties, possess almost complete immunity; (2) some strains of tobacco which have been developed by selection from those plants which were not diseased when grown in badly infested fields; (3) American grapes, which are much more resistant than European varieties; (4) certain kinds of figs (for example, Celeste and Poulette are claimed to be less susceptible than other varieties); and (5) some strains of watermelon (most varieties are very susceptible). Hence, it is desirable that the less susceptible strains be grown wherever possible, since this not only reduces the number of nematodes present but also insures better crops.

As most of the above strains have been obtained by careful selection and breeding, it seems quite likely that other immune varieties can be developed in a similar way from crops which are now susceptible. Every farmer should be able to practice a simple selection, that is,

when any plants in an infested field come up to standard in every way, are especially vigorous, and show freedom from root-knot, they should be marked and their seeds harvested separately. These seeds should be planted on infested land and similar careful seed selection should be made from the resulting disease-free plants. More complicated breeding work, especially the crossing of immune upon susceptible varieties, is not advisable for the average farmer, on account of the time and money required.

As the most satisfactory and economical method of controlling root-knot depends upon the proper system of rotation with immune varieties of plants, it is highly important to keep pure the strains that are already known to be resistant. This can be accomplished by preventing their crossing with susceptible varieties. It is also important that new strains of resistant crops be developed.

SUMMARY.

A serious disease of plants known under the names of root-knot, root-gall, big-root, etc., causes immense damage in all except the most northern States of this country.

The parasite causing the disease is a minute nematode, or gallworm (*Heterodera radicicola*), which multiplies very rapidly under favorable conditions. The life cycle may be completed in about four to five weeks, and each female may lay as many as 500 eggs. When invaded by the worms, roots become enlarged, distorted, or deformed, resulting in a hindrance to the growth of the plant.

Root-knot flourishes best in light, sandy soils which are moist and warm. It can not thrive in heavy soils or in those that are constantly wet.

Most crops are susceptible to the attacks of the disease. Some, however, are resistant. The most important of these are the Iron and Brabham cowpeas, corn, barley, beggarweed, rye, redtop, sorghum, timothy, velvet bean, wheat, and winter oats.

The nematodes may be transported from one locality to another in many ways, as in the roots of growing plants, and by means of tubers, bulbs, and nursery stock. They can be carried from field to field by such agencies as running water and the soil which clings to agricultural implements, the feet of men, and the hoofs of animals.

The disease may be eliminated in greenhouses and seed beds when they are not being used by the application of steam under high pressure or by the introduction of uninfested soil into clean, whitewashed benches.

In ginseng plantations the nematode may be controlled by eliminating all diseased plants, steaming the soil, and replanting with either disease-free rooted plants or sterilized seed.

In orchards, ornamental gardens, etc., no entirely satisfactory method of control has been worked out. Cultivation and high fertilization may cause trees to overcome the trouble by inducing rapid growth. In cases of local infestation, badly diseased trees should be removed and the infested soil treated with formaldehyde before replanting with healthy stock. Do not plant susceptible cover crops, as they rapidly increase the number of nematodes. Never plant an orchard on land that is not known to be nematode free. Do not plant infested nursery stock on either clean or infested soil.

The most satisfactory method of combating the nematode in fields not planted to perennial crops is by the cultivation of immune crops for a period of two to three years and by carefully killing all weeds and susceptible plants in which the nematode can live. A desirable rotation is that where winter grains alternate with either Iron or Brabham cowpeas, velvet beans, or beggarweed. Care must be exercised to prevent running water, implements, animals, etc., from bringing the nematode from near-by infested fields. In ridding land of root-knot, plant only those crops which are known to be free from the disease.

Starving the nematodes by keeping the land free from all vegetation for two years is an effective control method, though often impracticable.

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